

# Numerical and experimental investigation for formability of friction stir welded dissimilar aluminum alloys

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**Abstract.** Automotive manufacturers have been trying to improve fuel efficiency without compromising the structural integrity and one of the ways to resolve the issue is to expand usage of tailor welded blanks (TWBs) in car body structure. Friction stir welding (FSW) is a joining process, which can be well fitted to obtaining aluminum tailored blanks when compared to other conventional joining processes. This paper presents an experimental and numerical study on TWBs produced by FSW with dissimilar aluminum 5083-H32 and 6061-T6 alloy sheets. The quality of the friction stir welded dissimilar joints was evaluated in terms of metallographic observations, hardness studies and tensile tests. Moreover, the local property changes in the weld regions were observed through digital image correlation (DIC) method. Formability of friction stir welded blanks was evaluated in the biaxial stretch forming mode using the limiting dome height (LDH) test. The failure location and the LDH values of the formed blanks were correlated to the hardness and local properties across the welds. The FE simulation of the LDH tests was also conducted incorporating Yld2000-2d anisotropy constitutive properties of the parent metal and further considering the properties of the non-homogeneous welded zone. The Marciniak-Kuczynski model was applied to predict the failure successfully in the FE model, and the results were validated with experimental data.

## 1. Introduction

The continuous growth in environmental and economic concerns has pushed automotive manufacturers to implement innovations to reduce vehicle emission, improve fuel economy without compromising the safety, structural integrity and crash performance of the vehicle. Lightweight materials have been increasingly applied to automotive parts because they could efficiently contribute to decreasing body weight [1]. Compared to conventional steels, aluminum alloys have lower density and larger specific strength, which makes it possible for aluminum parts to achieve reduction of weight without loss in strength [2]. However, there are two main factors restricting application of aluminum alloys to auto body parts. One is poor weldability and the other is lack of formability.

Poor weldability is attributed to less specific resistivity which interrupts such conventional welding processes as electrical resistance spot welding and gas metal arc welding. Much effort was invested to develop auxiliary methods to conventional welding processes for successful welds. A developed procedure seems not to be cost-effective, though, because major adjustment of process parameters is required each time to fabricate weld for different combinations of materials and a certain combination even failed to be welded especially for dissimilar sheets.



An alternative joining process is friction stir welding (FSW) process [3] which generates joint region by thermo-mechanical mixing. Heat and plastic work of materials was mechanically induced during FSW process by friction between the rotating tool and the materials, which enable to join the materials below their liquidus temperatures. Selection of material combinations to join become flexible for FSW process because joint quality is less affected by thermal and electrical properties varying with chemical composition of the materials. Therefore, application of FSW process is being expanded to assemble lightweight metal parts, especially for parts made with aluminum alloys.

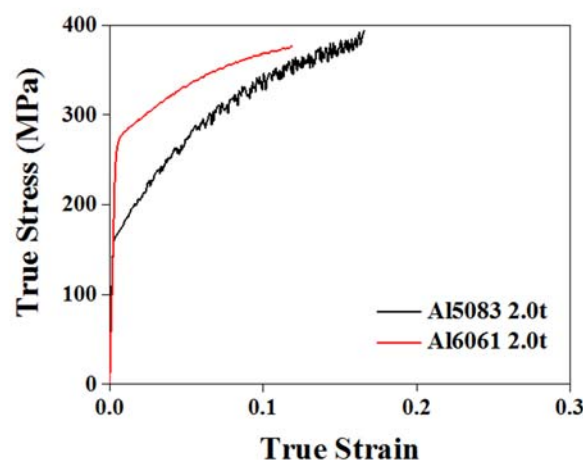
Use of tailor welded blanks (TWBs) for sheet metal forming parts [4] is being encouraged to enhance cost effectiveness. The forming procedure employing TWBs enable to reduce the number of process stages as well as to save loss of materials. Forming parts with TWBs of aluminum alloy sheets should require optimized process conditions different from those for conventional steel parts because of low formability and large anisotropy of aluminum sheets. Design of light weight parts is to be preceded by evaluation of forming characteristics.

This paper presents an experimental and numerical study on formability of TWBs produced by FSW with dissimilar aluminum 5083-H32 and 6061-T6 alloy sheets. The quality of the friction stir welded dissimilar joints was evaluated in terms of metallographic observations, hardness studies and tensile tests. Moreover, the local property changes in the weld regions were observed through digital image correlation (DIC) method. Formability of friction stir welded blanks was evaluated in the biaxial stretch forming mode using the limiting dome height (LDH) test. The failure location and the LDH values of the formed blanks were correlated to the hardness and local properties across the welds. The FE simulation of the LDH tests was also conducted incorporating Yld2000-2d anisotropy constitutive properties of the parent metal and further considering the properties of the non-homogeneous welded zone. The Marciniak-Kuczynski model was applied to predict the failure successfully in the FE model, and the results were validated with experimental data.

## 2. Experimental procedure

### 2.1. Materials

The Al-Mg alloy sheet of Al5083-H32 and the Al-Mg-Si alloy sheet of Al6061-T6 are selected as base material sheets. The thickness of Al5083 and Al6061 are identical as 2.0 mm. Anisotropy of both alloy sheets was evaluated by yield stress values (YS) and plastic strain ratios ( $r$ -values) through directional uniaxial tensile tests, in which the standard procedure of ASTM E8 was followed to measure the stress strain curves with the gauge length of 50.0 mm under the loading speed of 0.05 mm/s. True stress-true strain curves along the rolling direction are depicted in Figure 1 and measured values representing anisotropy are listed in Table 1.



**Figure 1.** True stress versus true strain curves for Al5083 and Al6061.

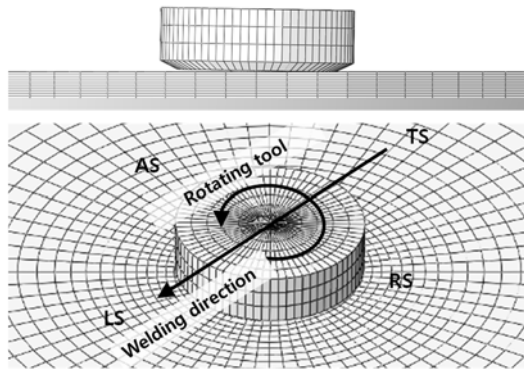
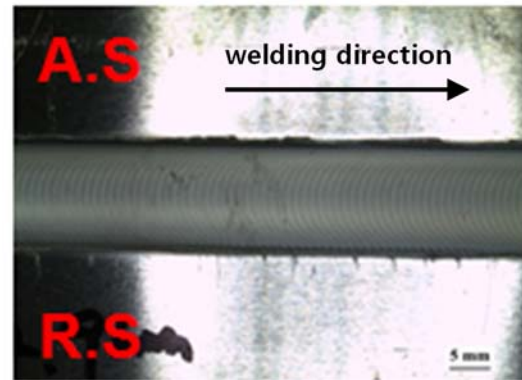
**Table 1.** Directional anisotropy of yields stress values and plastic strain ratios.

	YS <sub>0</sub>	YS <sub>45</sub>	YS <sub>90</sub>	r <sub>0</sub>	r <sub>45</sub>	r <sub>90</sub>
Al5083	259.2	241.0	242.7	0.6139	0.8735	0.6364
Al6061	268.2	255.8	260.0	0.6434	0.6467	0.7509

Unit of YS = MPa

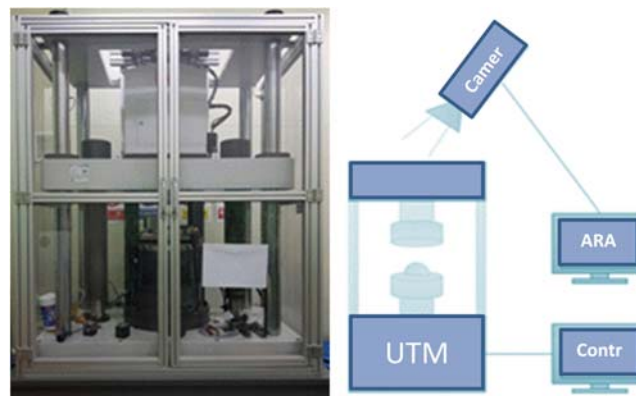
### 2.2. Friction stir welded tailor blank

FSW process was applied to fabricate the TWB of the dissimilar aluminum alloy sheets of Al5083 and Al6061. The dissimilar sheets were placed for butt type welding and became line-welded by advance of the rotating tool, as shown in Figure 2. With the plunge depth of 1.70 mm fixed, rotation speed of 1250 rpm and lateral speed of 500 mm/min were empirically selected as one of optimum parameter sets, which resulted in suppression of rough burr generation and enough stir depth and top surface without burr generation, as shown in Figure 3.

**Figure 2.** Schematics of FSW process.**Figure 3.** Top surface of the FSW seam.

### 2.3. Tensile test and limit dome height test

The tensile test of TWB was used to obtain variant mechanical characteristics over the weld region. The tensile test specimen was cut from the TWB as for the tensile direction to be perpendicular to the welding direction. The geometric dimensions and experimental conditions for the tensile test of the TWB sample are the same as those for the standard specimen of the base materials. Limit dome height (LDH) test was used to evaluate formability of the TWB since the specimen of LDH test is known to experience deformation in biaxial stretch mode which is generally observed in sheet metal forming. Following the standard of ASTM E2218, LDH test was carried out on 200 x 200 mm<sup>2</sup> sheets with respective punch radius and speed of 50.0 mm and 0.1mm/s. A hydraulic universal testing machine (UTM) was employed to perform tensile test and LDH test with aid of ARAMIS for real-time record of deformation by DIC method, as shown in Figure 4. The details at the DIC setting parameters are listed in Table 2.



**Figure 4.** Equipment ready for Limit dome height test.

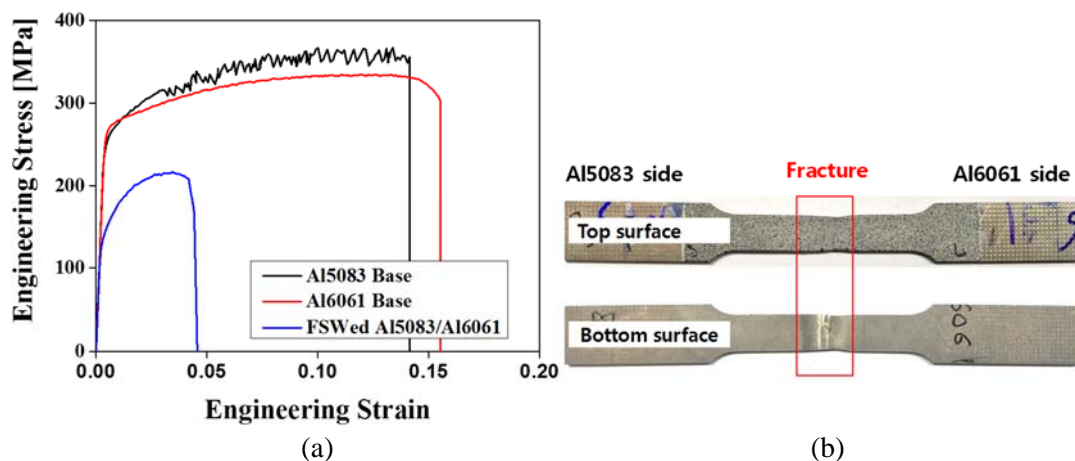
**Table 2.** DIC process parameters for measurement of local strain.

Facet size (pixel)	Facet field	Area of interest (mm <sup>2</sup> )	Frame rate (/s)
19 x 19	120 x 120	120 x 120	1

### 3. Results and discussions

#### 3.1. Mechanical characteristics of friction stir welded tailor blank

Robustness of TWB was investigated by metallographic observation, hardness measurement, and tensile test. The welded joint was cross-sectioned and hardness was measured over the section. With optical microscopic observation on the etched section, the measured hardness distribution indicates that mechanical properties represented by hardness are variant over the area of the welded joint and weld region is weaker than the base sheets. The weakness of weld region is also found out by tensile test results, in which there is degradation of both strength and ductility as shown in Figure 5. Furthermore, the local hardening curves of the weld region were analytically characterized based on local deformation data obtained by DIC method. Stress strain curves at the characteristic discrete point are presented in Figure 6.



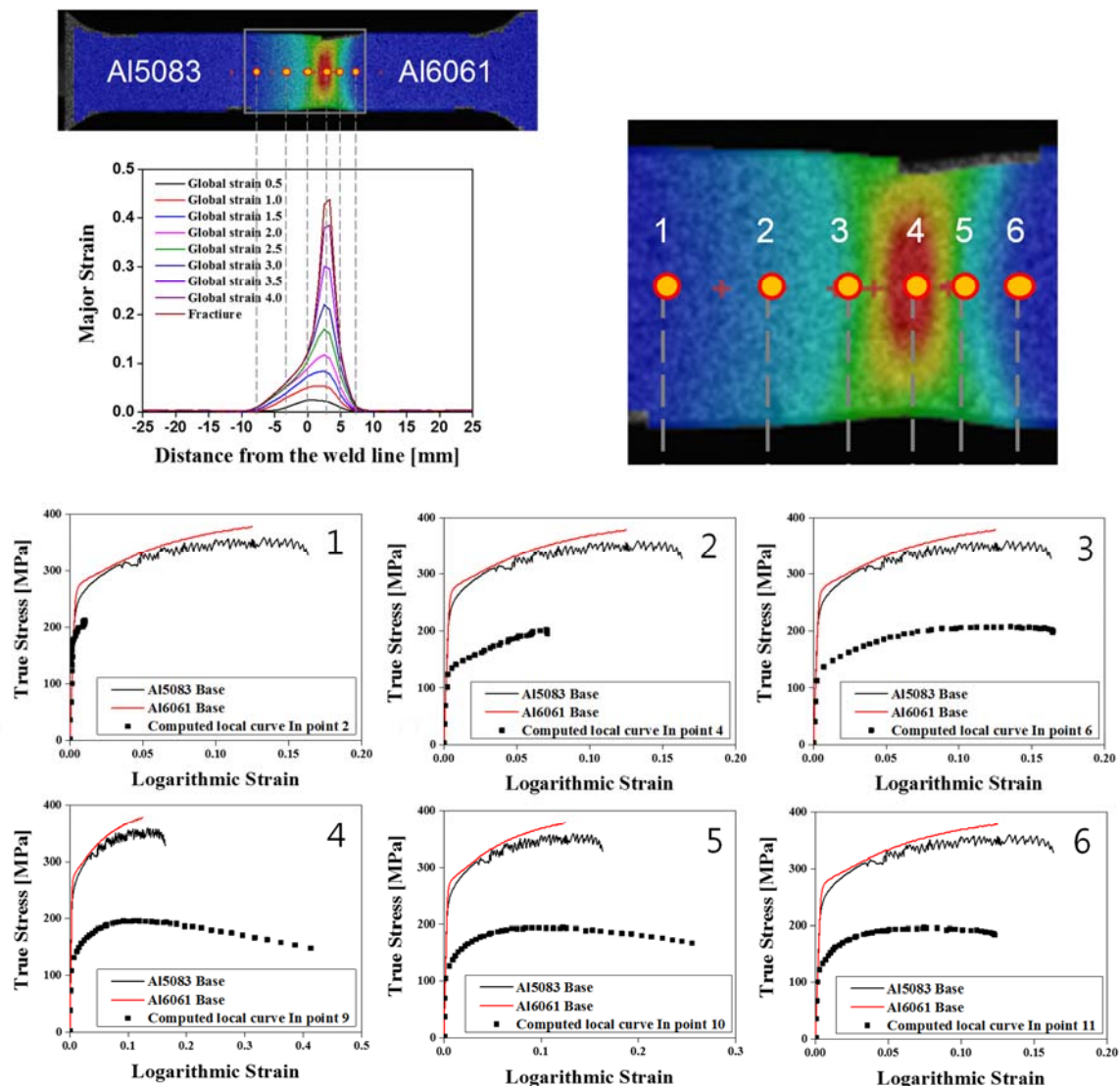
**Figure 5.** Tensile test results of TWB: (a) stress strain curves and (b) fractured specimens.

#### 3.2. Formability of friction stir welded tailor blank

Formability of TWB was evaluated by analysis of LDH test result. From real time measurement with DIC method, strain concentration was confirmed to develop in the weld region as punch continuously

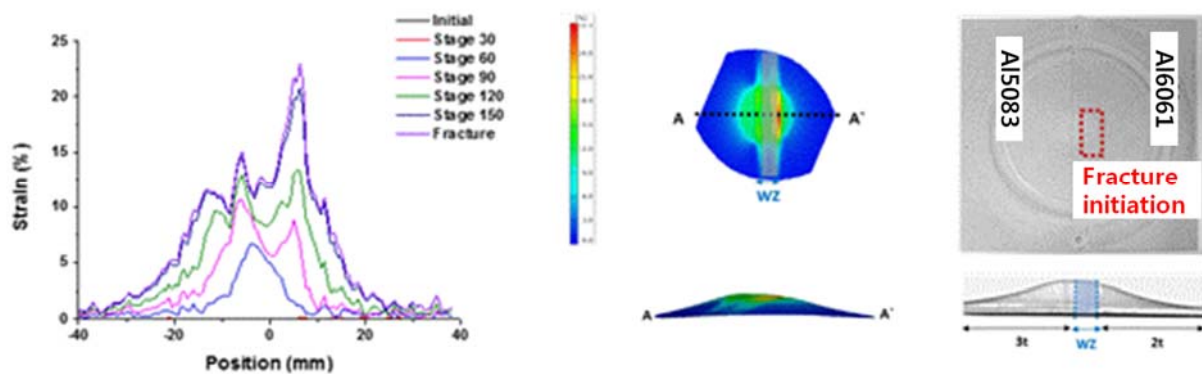
moved, as shown in Figure 7. Initial fracture occurred in the weld region close to the Al6061 sheet and the maximum site of major strain almost coincides with where fracture initiated, as shown in Figure 7. The region showing onset of fracture can be predicted by the local properties of the weld region because the fracture initiation during LDH test is at the site of the most degradation of the hardening curve presented in the previous section.

Furthermore, the finite element (FE) model was developed, which is applicable to formability prediction in other sheet forming processes. Considering the local properties of weld region, the Marciniak-Kuczynski (MK) model was used to obtain forming limit curve numerically. The FE simulation of LDH test was conducted together with incorporation of Yld2000-2d [5] anisotropic yield constitutive model for the base sheets. The model was validated by that the measured strain value showed little difference from the calculated one at the onset of fracture.



**Figure 6.** Major strain distribution and stress strain curves by analysis of DIC data.





**Figure 7.** Change of major strain distribution as rise of punch stroke leading to fracture initiation.

#### 4. Conclusions

Formability of the friction stir welded tailor blank was investigated for the dissimilar weld of the aluminum alloy sheets of Al5083 and Al6061. The local properties of the weld zone were calculated by analysis of the tensile test data including continuous change of strain field. The region showing the largest degradation of hardening was found to be in the weld region and it is closer to the Al6xxx sheet. In the same region, most strain concentration occurred in order to initiate fracture. LDH test was conducted for quantitative evaluation of formability in biaxial stretch mode. As the punch continuously moved, the weak region observed in the tensile test experienced strain concentration and triggered fracture in turn. Furthermore, the FE model was developed for formability prediction. M-K model was used to characterize forming limit curve in distinct region in the welded joint. Incorporating the anisotropy of the base sheets, the develop model was applied to simulation of LDH test and was validated with the experiment. The developed model can be applied to optimization of various sheet forming process especially for TWB of lightweight metal sheets in the automotive industry.

#### References

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